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Cognitive node selection and assignment algorithms for weighted cooperative sensing in radar systems

Lingfeng (Stephen) Wang[1], Angela Doufexi[1], Chris Williams[2], and Joe McGeehan[1]
[1.] Centre for Communications Research, University of Bristol, Woodland Road, Bristol, BS8 1UB, U.K.
[2.] Used to be with Centre for Communications Research, University of Bristol

Abstract: For the radar spectrum to be shared efficiently a good sensing capability within a secondary cognitive communication system is required. In this paper, the swept radar's rotation mechanism is explored to improve the sensing performance. Several node teaming algorithms are proposed for cooperative sensing along with the use of weighted sensing algorithms in a swept radar scenario. These teaming algorithms are considered in respect of the mobile team node selection and the sensing task assignments of the team nodes. Performance results show that selecting appropriate sensing nodes to join the sensing-active team in different sensing cycles and exploring their frequency diversity (to perform the sensing task at the most suitable frequency sub-channels), yields a substantial improvement in performance. In addition, it is illustrated that proper node teaming algorithms should be chosen based on several key factors, including the characteristics of the primary signal and the sensing team node's computational capabilities.

I. INTRODUCTION

In order to improve the spectrum efficiency, the concept of 'Cognitive radio' was proposed in [1], which enables an increase in spectrum utilization through exploiting white space or bandsharing by introducing a more dynamic, flexible spectrum allocation strategy. An effective cognitive spectrum access algorithm requires efficient and reliable spectrum sensing functionality within the physical layer.

Cooperative sensing with bandsharing is considered in [2][3]. An in-depth analysis on the design of the cooperative spectrum sensing in a radar scenario for improving spectrum usage efficiency is also provided in [5][6]. In addition, for sensing node selection and deployment issues, Ghasemi analyses the node density control issue in [7]. Furthermore, Peh and Liang show in [4] that the optimum sensing performance is achieved by grouping those nodes having the highest received signal power on the primary spectrum to noise ratio (SNR). In [8], a protocol is proposed to keep the original network coverage with fewer on-duty nodes. Consequently, higher energy efficiency and lower signalling demand are achieved.

This paper will focus on team node selection and sensing task assignment on mobile available candidate nodes in a swept radar scenario. Previous work [6] has proposed a weighted cooperative sensing algorithm to improve the sensing performance, where sensing nodes are in a fixed scenario and therefore have time-invariant SNRs. In this paper, this work is extended to a scenario where mobile nodes explore their opportunistic access in a radar system with a rotating antenna. Consequently different sensing nodes have different SNRs at different time and possibly at different frequency sub-channels. Therefore, it is worthwhile to design a node teaming algorithm to effectively select the appropriate nodes to join the cooperative sensing team and optimally assign the team nodes to perform the sensing at different time and different frequency sub-channels to keep achieving the target sensing performance in a mobile scenario.

The rest of this paper is structured as follows. In Section II, the sensing scenario is presented and the features of both the primary system and secondary cognitive system are described. In Section III, a cooperative sensing team node selection algorithm and several team sensing assignment algorithms are proposed. Section IV discusses the performance results of the proposed algorithms, along with the weighted sensing algorithms by considering nodes' sensing credibility. Section V concludes the paper.

II. SCENARIO DESCRIPTION

A. S-band swept pulse radar

The main parameters of the pulse radars considered in this paper, based on several types of commercial (aeronautical radio-navigation and meteorological) and military radars [9], are shown in Table 1.

Parameters		Unit
Radar frequency	2.7	GHz
Pulse Repetition Time (PRT)	1000	μs
Pulsewidth	10	μs
3dB mainlobe width	1.4 (Cosine aperture distribution)	Degree
Pulse moduation	Linear Frequency Modulation	
Radar rotation period	4.8	Second

Table 1: Swept radar parameters

As most radar systems have a cosecant-squared elevation pattern (e.g. aeronautical radio-navigation radar), which radiates almost the same power along different elevation angles, exploring the opportunistic radar spectrum access along the elevation dimension is of no interest. Consequently a one-dimensional (horizontal) swept radar aperture distribution is considered here, the antenna pattern is given by [10],

$$E(\phi) = \int_{-\frac{a}{2}}^{\frac{a}{2}} A(z)\exp(j2\pi\frac{z}{\lambda}\sin\phi)dz \quad (1)$$

Where a is the width of the aperture in z-dimension. λ is radar wavelength. ϕ is the radar swept rotation angle and $A(z)$ is the radar aperture distribution. A Cosine aperture distribution is chosen as a typical parameter. Thus, its corresponding field-intensity pattern is expressed by [10],

$$E(\phi)=\frac{\pi}{4}\left[\frac{\sin[\psi+\frac{\pi}{2}]}{\psi+\frac{\pi}{2}}+\frac{\sin[\psi-\frac{\pi}{2}]}{\psi-\frac{\pi}{2}}\right] \qquad (2)$$

where $\psi=\pi(a/\lambda)\sin\phi$.

Unlike a generic communication system's transmitter that transmits its primary signal omnidirectionally at all times, the swept radar transceiver rotates its antenna 360 degree horizontally in a preset rotation period. e.g. 4.8s for air traffic control radars at airports; 20s for meteorological radars [9]. In addition, the transmission power of the first sidelobe of the radar is usually over 23dB below the mainlobe. This rotation mechanism makes the radar protection range/area (in which, secondary devices are forbidden to access the radar spectrum or only permitted to have very low transmission power due to the radar's protection criteria) not an omnidirectional circle but a mainlobe-led area which keeps rotating based on the radar rotation period. Therefore a radar spectrum spatial opportunistic access/sharing is worth investigating for spectrum efficiency purposes. From spectrum sensing perspective, obtaining a higher primary radar signal power by tracking the radar mainlobe can effectively increase the detection probability while reducing the false alarm probability in a limited sensing cycle time. From an opportunistic radar spectrum access viewpoint, avoiding accessing the radar spectrum when being swept by the mainlobe can dramatically reduce the radar protection range and/or increase the transmission power of the secondary cognitive device. The following proposed algorithms will make full use of the characteristics of the radar and, by enhancing the sensing performance, increase spectrum efficiency through reliable spatial opportunistic access to the radar spectrum.

B. Cognitive secondary communication system

A generic communication system with a spectrum sensing function is adopted as a cognitive secondary system in the radar spectrum, e.g. an OFDM-based system with sensing capability is suitable for opportunistic access as it allows a very flexible spectrum access on a subcarrier-by-subcarrier basis. The secondary system could operate on its licensed spectrum as a primary system while sensing the radar spectrum for opportunistic access as a secondary cognitive system. All the sensing information signalling is transmitted on its primary licensed frequency and will not interfere with the radar operation. In this paper, the communication terminals are called sensing nodes with a radar spectrum sensing function. Under the assumption of perfect noise estimation, energy detection is used in the sensing node as the local sensing processing technique. This assumption can be relaxed if some information about the structure of the primary signal, e.g. cyclic frequency, is available. Better sensing performance may be achieved by using more sophisticated sensing techniques such as cyclic feature detection [11] at the cost of increased complexity of the sensing nodes. The mobile speed of these sensing nodes is set to 3km/h and they experience a Rayleigh multipath fading ITU pedestrian B channel [12]. The swept radar scenario is shown in Figure 1.

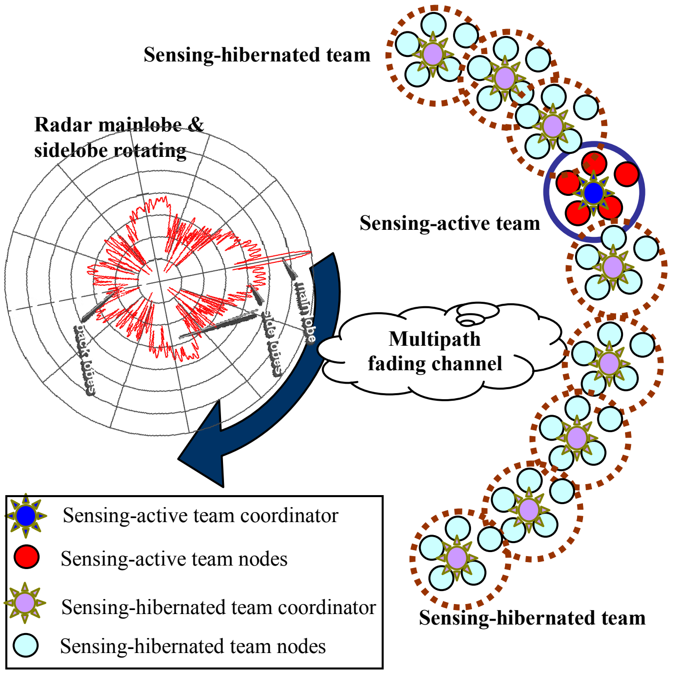

Figure 1: Mobile cognitive communication nodes' spectrum sensing in a swept radar scenario

Each sensing-active team node will perform the sensing by sampling the observations in the assigned primary spectrum (radar). The sampling duration is regarded as one ***sensing cycle***. Sensing decisions are made at the end of each sensing cycle. Considering the radar's parameters used in our MATLAB simulator (shown in Table 1), one sensing cycle is set as the duration of four cumulated radar pulses. One ***mainlobe sweeping period***, which is the time duration of the mainlobe sweeping on a sensing node (therefore a much higher received radar signal power), is calculated as 0.0186 second. This is equivalent to four sensing cycles. It is assumed that for each team node, its received SNR frequency response is unchanged during one mainlobe sweeping period.

III. Cooperative Sensing Team Node Selection, Sensing Assignment Algorithms

By exploring the time/spatial diversity in a swept radar scenario as shown in Figure 1, a sensing team selection algorithm is presented in section III.*A*. Several sensing assignment algorithms for team nodes are proposed in section III.*B*.

A. Selection algorithm of the sensing team

All the nodes in the coverage of a central controller (e.g. base station) can act as candidate sensing nodes. The central controller has some basic knowledge of the radar (primary system), e.g. opportunistic access-permitted spectral ranges (S-band), which region in the coverage of the central controller is sensing-requisite, but it has no knowledge of detailed radar operation information. As shown in Figure 1, those nodes being selected as part of the sensing team will be classified as either in a:

- Sensing-active state (nodes performing sensing tasks)

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- Sensing-hibernated state (nodes not performing sensing tasks)

Only one team is 'sensing-active' in one sensing cycle. A selection procedure of the sensing-active team and its team nodes is as follows:

1) A central controller will select a number of distributed nodes as sensing team coordinators, depending on the state of the nodes (e.g. battery state, signalling channel state, complexity capability) and their positioning information (available by positioning system, e.g. in-built GPS gadget). Team coordinators will take the duty of selecting the team nodes; assigning team nodes to perform sensing at different frequency sub-channels for enhancing the sensing performance; collecting their local decisions and making the global decision on whether the radar spectrum is accessible.

2) The selected team coordinators will transmit a local low-power teaming-request signal to their neighbouring nodes (shown in Figure 2). Only the nodes which are capable of receiving this request are eligible to join the sensing team of the team coordinator. This low power teaming-request mechanism can guarantee the effective distance spread among the team nodes. Thereby it leads to a highly effective and efficient sensing process.

3) All team coordinators send their preliminary SNRs to the central controller, which then decides which team is in a sensing-active state. The remaining teams stay in sensing-hibernated state. These preliminary SNRs are measured in very limited time duration, which is not good enough for making a good global sensing decision. However, these measurements are helpful to provide a reference to determine the teams' sensing state (sensing-active or sensing-hibernated) for initializing the following team sensing process.

4) A sensing-active team starts to perform cooperative sensing to achieve the maximum sensing team SNR (average SNR of the team nodes) and required sensing performance. When the global sensing decision is made at the end of each sensing cycle (as shown in Figure 3), the sensing-active team coordinator shares the updated radar spectrum state with the sensing-hibernated team nodes through the sensing-hibernated coordinators, whose teams perform the sensing task in preceding/following sensing cycles.

5) At the end of the each sensing cycle, the sensing-active team coordinator informs its neighbouring team coordinator to switch into sensing-active state for the next sensing process.

In order to make sure the sensing results are timely ('unexpired'), the sensing process should be performed periodically. The term '***sensing period***' is introduced in [13], and defined as the time interval between two continuing sensing process. The sensing period determines the maximum time during which the secondary cognitive device will be unaware of the changes of the radar protection range and hence may harmfully interfere with it. In our scenario as shown in Figure 3, the sensing period is the update period of the sensing-active team. It mainly depends on the primary system's characteristic, e.g. radar rotation period, and has to be set for the safe operation of radar systems by the regulator. In our simulator, the sensing period is set as one mainlobe sweeping period.

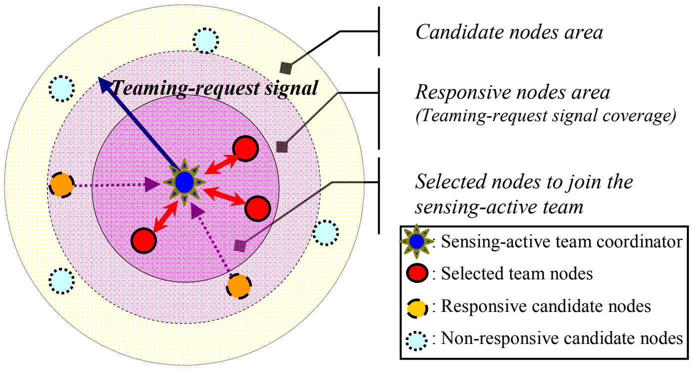

Figure 2: Sensing-active team node request and selection process

As shown in Figure 3, from the perspective of the secondary system it is desired to maintain the sensing cycle time well below the sensing period in order to maximize the time available for opportunistic radar spectrum access transmission. For the same sensing requirement, compared to single node sensing, a team cooperative sensing can offer the same performance in a much short sensing cycle time [6]. In addition, the sensing cycle time can be prolonged for a better sensing performance or to reduce the complexity of the sensing team nodes. However, the opportunistic access time is shrunk accordingly in the case of a fixed sensing period as illustrated in sensing period 2 (Figure 3).

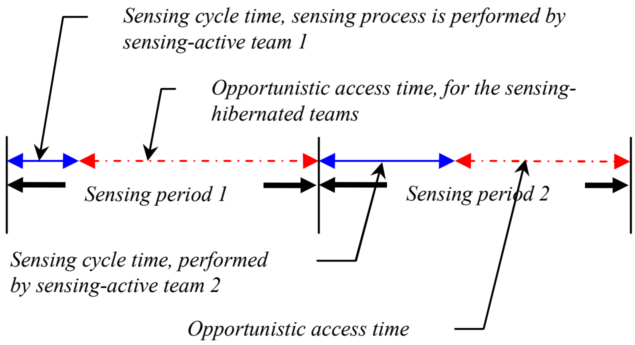

Figure 3: Sensing & opportunistic access process flow

To achieve the best sensing performance effectively at all times, the sensing-active team coordinator will select the highest-n SNR nodes (n=6 in our simulator) from the teaming-request responsive candidate nodes, at the current sensing cycle, to join the sensing team.

In the case where the number of responsive candidate nodes increases dramatically, the preliminary state reporting mechanism (by which candidate nodes transmit their state, e.g. preliminary SNRs, to the team coordinator) will create a heavy signalling traffic. This issue may be addressed by setting a credibility threshold for the candidate nodes. Only the nodes, achieving a higher credibility (e.g. high preliminary SNR, low movement speed) than the threshold, may be allowed to respond to the team coordinator. As illustrated in Figure 2, the team coordinator may specify a tunable threshold through its broadcast channel in order to meet different priorities of the sensing requirements, such as a strict signalling traffic limitation or a guarantee on a certain amount of sensing candidate nodes supply. Furthermore, instead of creating new MAC frames to exchange these teaming request-respond signalling message, signalling in the physical layer can be employed as suggested in [14].

B. Sensing assignment algorithms for the sensing-active team

The selected team nodes can further explore the frequency diversity of the received SNR to make local sensing decisions on the most suitable frequency sub-channels. By considering different criteria, in terms of whether to maximize the sensing performance or to consider the node's computational complexity, 3 assignment algorithms are proposed in this section to achieve a better sensing team SNR for a required cooperative sensing performance. In the case of a frequency-flat scenario, where the radar signal is considered as a narrowband signal (e.g. unmodulated radar signal), the highest-SNR can be obtained in the centre of the radar spectrum. In the case of a frequency-selective scenario, e.g. a multi-path channel and wideband Linear Frequency Modulation (LFM) radar signal, the SNRs of the sensing nodes vary both in the time domain and the frequency domain. However, it should be noted that the received SNR is assumed to be time-invariant during one mainlobe sweeping period.

Figure 4 shows the frequency diversity of the received SNR (noise power is normalized to unity). Since the LFM radar signal bandwidth is much wider than the channel coherence bandwidth, the highest SNR possible is located at a frequency sub-channel randomly within the radar bandwidth. If more sensing bandwidth and therefore increased frequency diversity is available, then by sensing at the highest SNR frequency sub-channel we can obtain a better sensing performance.

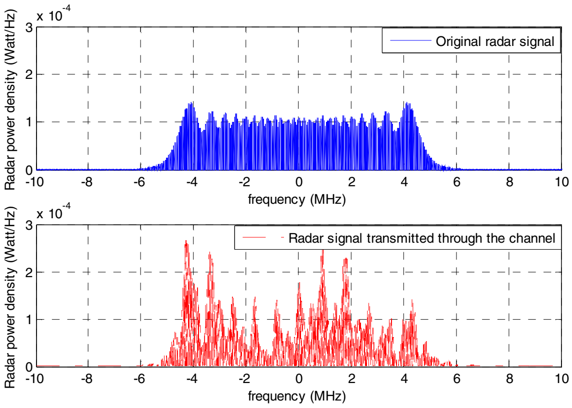

Figure 4: Frequency response of the LFM radar (bandwidth=10MHz) after transmitted through the ITU channel (node average received SNR = 0dB)

- **MaxSense algorithm**

In this algorithm, each team node selects the frequency sub-channel that has the highest SNR along its frequency domain and makes its local sensing decision at the chosen frequency sub-channel, then transmits the local decision to the team coordinator which will make a final sensing decision. This algorithm can offer the highest average team SNR at the end of each sensing cycle. However, if only energy detection is used and a certain frequency sub-channel suffers interference from a non-primary signal (e.g. malicious signal as described in [16]), the team nodes may incorrectly choose this frequency sub-channel to do the sensing. Consequently, this action will result in an unacceptable false alarm probability repeatedly. We term this issue as the double-false alarm problem.

- **EasySense2 algorithm**

The EasySense2 algorithm ensures each team node make its local sensing decision at different sub-channels while still maintaining a good sensing performance. To significantly reduce the signalling cost, instead of transmitting the SNRs of all frequency sub-channels from all n team nodes, each team node chooses only to report the sub-channels of the highest-m SNR ($m>n$) to the team coordinator. As m sub-channels reported by team nodes are less likely fully coincidental, there exists $(m+p)$ columns in SNR matrix, p 'null's are filled in corresponding matrix elements. Then the team coordinator executes the EasySense2 assignment algorithm as shown in the below flowchart. A 'double frequency candidate pools' mechanism is introduced by collecting the frequency sub-channels which the node having the 1st or/and 2nd highest SNR is indexed to. After receiving the assigned sensing sub-channels from the team coordinator, team nodes make the local decisions and send them back to the coordinator, which then makes the final sensing decision.

EasySense2 algorithm *(Performed by sensing team coordinator)*

1) Collect & build up team nodes SNR matrix. (n Rows: team nodes, $m+p$ Columns: frequency sub-channels, $m>n$)
2) For each sub-channel, select the indices of the nodes which have the 1st or/and 2nd maximum SNR on this sub-channel
3) For each team node, set up the 1st and 2nd frequency candidate pools by collecting the sub-channels to which this node is indexed in step 2)
4) For each node, select the sub-channel of the maximum SNR in its 1st and 2nd candidate pool respectively as the 1st and 2nd sub-channels for the node (If no candidate, set as zero)

If SNR of 1st sub-channel >= SNR of 2nd sub-channel
  If 1st sub-channel is non-zero
    Do *Select 1st sub-channel as the sensing sub-channel*
      Build/update the sense-idle frequency pool
  Else *Skip to Idle-node 2nd round assignment process*
  End
Elseif SNR of 1st sub-channel < SNR of 2nd sub-channel
    Do *Team coordinator sorts nodes' SNRs of 2nd sub-channels in descending order. Node with the highest SNR of 2nd sub-channel has the priority to select in the sense-idle frequency pool first*
  If 2nd sub-channel of the node has not overlapped with previous assigned nodes' sub-channels
    Do *Select 2nd sub-channel as the sensing sub-channel*
  Elseif 1st sub-channel is non-zero and non-overlapped
    Do *Select 1st sub-channel as the node's sensing sub-channel*
  Else *Skip to Idle-node 2nd round assignment process*
  End
End

Idle-node 2nd round assignment process: For the sensing-idle node after the above assignment process, choose the sub-channel of the highest-SNR in the available frequency pool, based on a non frequency sub-channel overlapped principle.

- **Hungarian Algorithm (HA) algorithm**

By introducing the Hungarian Algorithm [15] (a combinatorial optimization algorithm which solves assignment problems) into the node sensing assignment algorithm, the node assignment procedure in the sensing team converts to a maximized overall combinatorial SNR problem. This sensing assignment algorithm offers the optimal overall SNR sensing environment by making full use of the frequency diversity while ensuring that the nodes avoid sensing a primary signal at an overlapping frequency sub-channel in order to solve the double-false alarm problem. However this optimal method requires high computational complexity in the sensing team coordinator which needs to calculate and assign the sensing frequency sub-channels.

IV. NODE TEAMING PERFORMANCE EVALUATION

A. Selection of the sensing-active team

This section presents the performance results obtained in the simulator by using the team node selection algorithm described previously. It is assumed that each node receives the same SNR, e.g. 0dB, when being swept by the radar mainlobe. The distance spread between adjacent team nodes ranges from zero radar mainlobe angle width (0 degrees) to one radar mainlobe angle width (1.4 degrees). As can be seen in Figure 5, *n* highest-SNR nodes are chosen to join a sensing-active team in each sensing period (e.g. *n*=6 in our scenario). A suitable number of team nodes should be determined by considering the availability of the responsive candidate nodes, as well as their sensing signalling cost. Although the team SNR decreases when the distance spread between adjacent team nodes increases, 6-node sensing teams can still achieve much higher team SNRs for the required sensing performance, compared to the SNR received by a single node which only has a peak SNR during the mainlobe sweeping period.

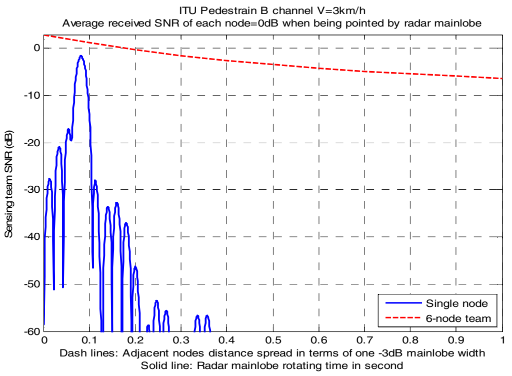

Figure 5: Achievable Team SNR by using team node selection algorithm

In a swept radar scenario, by updating the sensing-active team for each sensing period, the optimized sensing performance can always be reached. Sensing fairness is considered by introducing a sensing information-sharing mechanism. At the end of each sensing cycle, the sensing-active team coordinator will share the updated radar spectrum state with the sensing-hibernated team nodes. From a cognitive opportunistic access perspective, it means that these sensing-hibernated nodes can choose to access the radar spectrum at a higher transmission power because they are not being swept by the radar mainlobe and therefore cause less interference to the radar. By using the sensing information-sharing mechanism, all the sensing participants have knowledge of the radar state at all times although they only need to perform the sensing task at a certain sensing cycle. Therefore, it is quite fair for all nodes to do the sensing contribution and share the spectrum access opportunities at different sensing periods as long as their cognitive transmission will not cause unacceptable interference to the radar.

B. Sensing assignment for the selected team nodes

The following analysis is based on the assumption that the team nodes have 5MHz single side sensing bandwidth, which can cover the entire radar signal bandwidth. Figure 6 shows the Receiver Operating Characteristic (ROC) performance comparison among 4 different assignment algorithms in combination with 2 sensing algorithms (SNR_{direct} weighted sensing algorithm and standard [non-weighted] sensing algorithm). For the SNR_{direct} algorithm, after collecting the local decisions u_i from N team nodes, the global sensing decision u_0 is made by,

$$u_0 = \begin{cases} 1 & \sum_{i=1}^{N} W_i \times u_i \geq K \\ 0 & \sum_{i=1}^{N} W_i \times u_i < K \end{cases} \tag{3}$$

It declares a radar exists if $u_0 = 1$. $K = 0$ for the MAJORITY fusion rule. Weighting factor W_i is the linear-normalized SNR value for each team node. The basic concept of this algorithm is that the nodes having better SNRs (therefore better sensing credibility) contribute more in the global decision making.

As shown in Figure 6, for the same average team SNR and in combination with the standard sensing algorithm, the HA algorithm offers almost the same sensing performance as the MaxSense algorithm besides guaranteeing that there are no same frequency sub-channels used by two different nodes at the same sensing cycle, substantially solving the double-false alarm problem. As expected, the EasySense2 algorithm offers a slight worse sensing performance compared to the HA and MaxSense algorithms while only requiring a slight increase in computational complexity over the MaxSense algorithm (and a much lower computational complexity than the HA algorithm) as shown in Figure 7. Furthermore, EasySense2 shows significantly better performance than using TimedomainSense algorithm which performs the sensing without exploiting the frequency diversity. As confirmed in Figure 6, the SNR_{direct} weighted cooperative sensing algorithm provides a superior sensing performance to the standard cooperative sensing algorithm regardless of which sensing assignment algorithm is chosen. Furthermore, by using the SNR_{direct} weighted sensing algorithm, the introduction of the weighting factors (nodes' sensing credibility) for the sensing algorithm effectively compensates for the loss in the sensing performance resulting from the low-complexity EasySense2 algorithm, therefore making the performance of the EasySense2 algorithm close to high-complexity HA algorithm. Consequently, under the limitation of the node computational complexity, the EasySense2 algorithm can be chosen to offer a competitive sensing performance in combination with the weighted sensing algorithm.

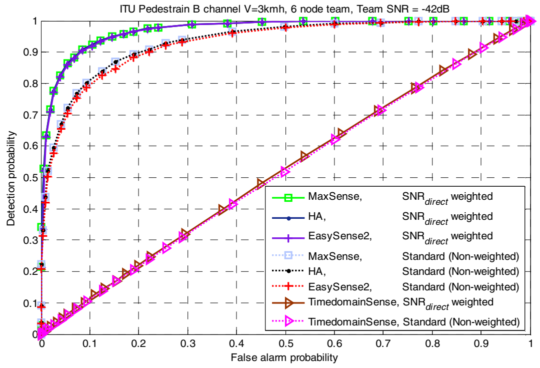

Figure 6: The ROC performance of different sensing assignment algorithms combined with SNR$_{direct}$ and standard sensing algorithms

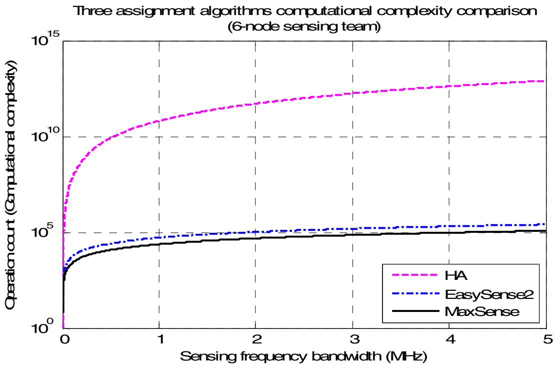

Figure 7: Comparison of the computational complexity among sensing assignment algorithms

V. CONCLUSION

In this paper, several node teaming algorithms have been considered for cooperative sensing in a mobile scenario. These algorithms are then presented in terms of the team node selection in the time domain and the sensing assignments of the team nodes in the frequency domain. For the team node selection, the proposed algorithm effectively updates the sensing-active team and selects the team nodes in a swept radar scenario. Consequently the maximum sensing team SNR can be obtained.

When it comes to the team node assignment performance, the MaxSense algorithm has the lowest complexity and the highest average team SNR, which consequently leads to a high sensing performance. However it is vulnerable to the 'malicious signal' attack due to the potential double-false alarm problem. The Hungarian Algorithm (HA) algorithm which maximizes the overall combinatorial SNR of the available nodes offers almost the same sensing performance as the MaxSense algorithm. In addition, at the price of high complexity, it effectively solves the double-false alarm problem that may happen in the MaxSense algorithm by assigning nodes to perform the sensing task at different frequency sub-channels in one sensing cycle. To reduce the computational complexity on the sensing-active team coordinator and the corresponding power consumption, the EasySense2 algorithm is proposed to achieve a good sensing performance, which is close to the performance of the MaxSense and the HA algorithms. Thus, the EasySense2 algorithm offers a good solution to the trade-off between high sensing performance and low computational complexity, meanwhile solves the double-false alarm problem. In addition, the introduction of the weighted sensing algorithm that considers each team node's sensing credibility leads to a satisfactory sensing performance even using low-complexity assignment algorithm which relaxes the team coordinator's complexity requirement. Hence the key issue is to select the most suitable cognitive node teaming algorithm along with the weighted sensing algorithm by considering the sensing performance, the characteristics of the primary signal and the secondary team coordinators' computation capabilities.

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